

**TWO-PHASE COOLING APPARATUS**  
**AND METHOD**  
**FOR AUTOMATIC TEST EQUIPMENT**

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**FIELD OF THE INVENTION**

The invention relates generally to automatic test equipment, and more particularly a two-phase cooling apparatus and method for cooling electronic assemblies disposed in a semiconductor tester testhead.

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**BACKGROUND OF THE INVENTION**

Automatic test equipment plays a pivotal role in the manufacture of semiconductor devices. The equipment, often referred to as a tester, typically provides at-speed functional verification of semiconductor devices at the wafer level and/or packaged device level. Ensuring that individual devices work properly before  
15 implementation in a higher assembly is critical to the commercial acceptance of a device.

As semiconductor devices become more complex, the ATE sub-systems required to test them correspondingly rise in complexity. Even more problematic is the rise in high-density, high-power devices. Often, high-power semiconductor  
20 devices collectively consume several hundred watts during peak operating conditions.

Conventional ATE typically employs a mainframe console or rack and a testhead. The testhead serves as a somewhat mobile housing for the channel electronics. The testhead is mobile in the sense that it may be manipulated along any one of six-degrees of freedom into a position proximate the device-under-test (DUT)  
25 to minimize signal delays between the ATE electronics and the DUT. Further, the testhead includes slots for positioning a plurality of circuit boards that mount the ATE channel electronics (often called "pin electronics"). In a sense, the testhead is a specialized card cage.

Conventional channel cards typically require some form of cooling. The art is  
30 replete with air cooled systems and liquid-cooled systems for use in semiconductor testheads. Examples of air cooling systems are found in U.S. Patent Nos. 6,184,676, 6,078,187, 5,952,842, 5,767,690, 5,644,248, and 5,978,218. Liquid cooling systems are typically employed in the form of cold plates or modules that attach to high-power boards. Two examples are described in U.S. Patent Nos. 6,052,284 and 6,081,428.

Conventional liquid cooling modules and cold plates are typically employed as single-phase systems. In other words, the liquid coolant remains as a liquid over the normal operating range of the system. Generally, heat is conducted from the generating component through the container wall into the liquid coolant, which then is transported by piping to a chiller where the heat is dissipated to air. In some cases, the coolant exchanges heat with temperature-controlled facility water.

While the conventional single-phase liquid cooling systems described above work well for their intended purposes, the heat transfer rate can still be too low due to the limited flow and pressure capacity of the liquid pumping systems, particularly for IC components with a relatively high heat flux. Larger coolant volume flow rates are undesirable for electronic systems striving to maintain a small footprint, since that implies much larger pumps which translates into overall larger cooling systems. Alternatively, decreasing the system pressure drop by increasing the plumbing sizes also negatively affects the system and card-cage packaging.

In an effort to provide for additional cooling capacity while maintaining a small footprint, those skilled in the art have employed two-phase cooling systems. Generally, these systems employ a low boiling point coolant that is circulated in close proximity to an electronic device. The coolant can be completely or partially vaporized (i.e. boiled) by heat dissipated by the electronic component. The coolant then travels to a remotely disposed condenser. In the condenser, the portion of the coolant that is vapor is converted back into a liquid. The liquid may further be subcooled depending on the overall cooling capacity of the condensor. The liquid is then returned to the heat-dissipating component so that the boiling/condensing cycle can be repeated.

One example of a two-phase cooling system is disclosed in U.S. Patent No. 6,519,955 by Marsala. This system provides a plurality of locally disposed cold plates that thermally contact respective electronic assemblies. The cold plates receive a single phase liquid coolant and distribute the coolant proximate the electronic device. As heat from the device boils off some of the coolant, the resulting two-phase mixture is discharged away from the cold plate into a remote vertically disposed vapor/liquid separator. The vertical nature of the separator enables the force of gravity to effect separation of the liquid from the vapor. The separated vapor is then directed to a remotely positioned condenser, where it is converted back to liquid. The separated liquid and converted liquid is then fed back to the pump and redistributed through the system.

While this cooling scheme appears beneficial for its intended applications, the gravity-based separation aspect is problematic for instances where the system such as automatic test equipment may lie in non-vertical orientations and the separator is mounted to the testhead. What is desired and as yet unavailable is a centralized two-  
5 phase cooling apparatus, system and method insensitive to testhead orientation. The two-phase cooling apparatus, system and method of the present invention satisfies this need.

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## **SUMMARY OF THE INVENTION**

The two-phase cooling apparatus and method of the present invention provides a cost-effective way to provide high capacity liquid cooling for a semiconductor tester testhead.

5           To realize the foregoing advantages, the invention in one form comprises a two-phase cooling apparatus for cooling an electronic assembly. The apparatus comprises an evaporator having a single-phase inlet for receiving a single-phase liquid coolant and a two-phase outlet for discharging a two-phase coolant. A local condenser is disposed proximate the evaporator and has a two-phase inlet coupled to the  
10   evaporator outlet. The local condenser includes a single-phase liquid coolant outlet. The apparatus further includes a pump having an output coupled to the evaporator inlet, and an input coupled to the local condenser outlet.

          In another form, the invention comprises a method of cooling electronic board assemblies in automatic test equipment. The method comprises the steps of pumping  
15   a single-phase liquid coolant onto the electronic assembly; exchanging heat proximate a first electronic device on the electronic assembly with the single-phase liquid coolant, and vaporizing a portion of the single-phase liquid coolant to form a two-phase coolant; condensing the two-phase coolant back to a single-phase liquid coolant; and routing the condensed single-phase liquid coolant off the electronic  
20   assembly.

Other features and advantages of the present invention will be apparent from the following detailed description when read in conjunction with the accompanying drawings.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

The invention will be better understood by reference to the following more detailed description and accompanying drawings in which

FIG. 1 is a block diagram of a two-phase cooling apparatus;

5        FIG. 2 is a block diagram of a centralized two-phase cooling system employing the two-phase cooling apparatus of Figure 1;

FIG. 3 is a cross-sectional view of a heat exchanger for use in the two-phase cooling system of Figure 1;

10       FIG. 4 is a block diagram similar to Figure 1 and illustrating a single-phase cooling path disposed in parallel with the two-phase path;

FIG. 5 is a block diagram of an alternative embodiment of the two phase cooling system shown in Figure 1; and

FIG. 6 is a block diagram of a further alternative embodiment of the two-phase cooling system shown in Figure 1.

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## DETAILED DESCRIPTION OF THE INVENTION

The two phase cooling apparatus, system and method described herein provides a means to selectively apply two-phase cooling to electronic assemblies such as instrument boards employed in a semiconductor tester testhead. By enabling the use of two-phase cooling in the manner described more fully below, lower cooling costs and smaller packaging would be realized by not requiring larger capacity pumps and cooling lines.

Referring first to Figure 1, the system generally feeds a single phase (liquid) coolant onto one or more electronics boards either directly or within an attached cold plate, and provides for two-phase cooling (boiling or evaporation) of an electronic device 57 between the board inlet and outlet points 55 and 56, respectively. The resulting two-phase mixture is condensed on-board, and fed back to the centralized distribution system. The following sections illustrate specific embodiments in which the on-board condensing can be achieved using a condensor, a single-phase (liquid) fluid, or by sub-cooled boiling. In all cases, the use of single-phase refers to a fluid in a liquid state but not necessarily at saturated conditions.

Referring now to Figure 2, one embodiment of a centralized two-phase cooling system 11 using a local condensor is illustrated for use with automatic test equipment, generally designated 10. The system includes a liquid coolant source 12, such as an in-line reservoir capable of supplying a dielectric liquid (such as HFE-7100 manufactured by 3M) to a coolant pump 14. The pump includes an outlet 16 that provides pressurized fluid to a supply manifold 18 disposed in the testhead 20 (in phantom).

Further referring to Figure 2, a plurality of single-phase inlet lines 22, 24 are distributed to spaced apart testhead slot locations (not shown) to enable selective connection to respective electronic board assemblies 26, 28. While only two board assemblies are shown for clarity, the testhead may include any number of boards to support whatever semiconductor device is being tested. A plurality of single-phase outlet lines 34, 36 receive discharged single-phase coolant from the board assemblies and feed it to an outlet manifold 32. The outlet manifold, in turn, directs the heated effluent a heat exchanger 15. The heat exchanger couples to a facility chiller (not shown) to exchange heat between the heated effluent and a facility source of water. The output of the heat exchanger is then fed back to the coolant reservoir 12 to complete the cooling loop.

With continued reference to Figure 2, each electronic board assembly 26, 28 includes one or more electronic devices (not shown) that generate a substantial amount of heat. In order to sufficiently cool for example a particularly high-power device, an evaporator 40 is disposed in fluid communication with the single-phase coolant inlet 22 and positioned proximate the electronic device to effect two-phase heat transfer. The evaporator partially vaporizes the single-phase coolant into a two-phase fluid. A two-phase fluid line 42 couples the outlet of the evaporator to the inlet of a locally disposed condenser 44. The output of the condenser connects to the single phase discharge line 34. The condenser cooling source is not explicitly shown in Figure 2 but can be provided by any number of methods, such as those described with reference to Figures 3 and 4.

Figure 3 illustrates one embodiment of an air-cooled condenser 44 suitable for use with the system of Figure 2. This condenser comprises a heat spreader plate 50 formed with a plurality of cooling channels 52 for the two-phase coolant coming from line 42 (Figure 2). The heat dissipates off the topside surface with an array of spaced-apart cooling fins 54. The geometric features of the condenser are sized appropriately to ensure the two-phase coolant is condensed to a single phase, a task familiar to those skilled in the art.

In operation, a plurality of electronic board assemblies are employed in the testhead, each including respective inlet and outlet cooling lines that tap into the supply and return coolant manifolds 18 and 32. With the tester operating to stimulate and capture test signals from a device-under-test, the electronic board assemblies 26, 28 dissipate large amounts of heat through various integrated circuit devices. This heat is transferred from the devices via the proximally located evaporators 40 to the coolant, creating a two-phase fluid mixture in the coolant line. This mixture is routed from the evaporator through the short two-phase line 42 to the condenser 44, where the mixture returns to a single phase liquid. The liquid is then discharged through the single-phase outlet line 34 to the outlet manifold 32, and into the heat exchanger 15 for cooling and eventually directed back to the coolant reservoir 12.

An important aspect of this cooling scheme involves the local on-board action of condensing the two-phase fluid, and routing the resulting single-phase liquid back to the centralized cooling system 11. By having a relatively close proximity between the point at which the two-phase fluid is condensed and the evaporator 40, the two-phase mixture flow can be controlled to a high degree independent of any gravity effects from, for example, an inverted testhead.

With reference to Figure 4, in an alternative embodiment, the instrument board 26 shown in Figure 2 includes the single-phase supply coolant 22 delivering liquid to the evaporator 40 and also a portion through fluid line 60 to the condensor 44. In this case, the condensor 44 is essentially a compact liquid-to-liquid heat exchanger for which many designs exist familiar to those skilled in the art of heat exchanger design. The two-phase coolant 42 and the single-phase coolant 60 are kept separated throughout the condensor 44 and merge again at a point when both are single phase (liquid) which in this case is shown external to the condensor 44 as area 65 (in phantom), which practically can be a Tee or Wye fitting. In practice the two-phase coolant line 42 is kept very short, for instance less than one inch.

Referring now to Figure 5, in a further embodiment, the instrument board 26 introduced in Figure 2 is again shown, but without a separate condensor. In this embodiment, sub-cooling the evaporator 40 has sub-cooled coolant entering it thereby allowing for rapid condensation of the two-phase mixture along a predetermined length of line 70. In operation, as the two-phase fluid leaves the evaporator 40 and flows along the line 70, the heat load and heat flux dramatically diminish and the fluid stops boiling and the vapor is condensed to a single-phase liquid state.

Referring now to Figure 6, the instrument board 26 introduced in Figure 2 is again shown also without a separate condensor. In this embodiment, the single-phase supply coolant 22 delivers a first portion to the evaporator 40 and a second portion 81 to the two-phase mixture 42 exiting the evaporator. The blending of a sufficient amount of the single-phase coolant 81 with the evaporator discharge 42 can condense the two-phase evaporator discharge 42 resulting in a single-phase liquid 34 leaving the board 26.

As noted above, one of the primary applications for the two-phase cooling apparatus described above involves implementation in a semiconductor tester testhead. Testheads are often oriented along several axes, and even inverted in some situations. Employing a pump 14 (Figure 1) in the two-phase apparatus ensures constant availability of coolant even in extreme testhead orientations.

Those skilled in the art will appreciate the many benefits and advantages afforded by the present invention. Of significant importance is the enabling of two-phase cooling for use in automatic test equipment that reduces cooling costs by increasing liquid cooling capacity. Also beneficial is the localized condensing of the two-phase fluid on the board to restore the two-phase fluid from the evaporator to a single-phase liquid over a relatively short distance. This feature addresses any



potential gravity issues that might result from the testhead being oriented in an extreme manner and detrimental flow distribution effects due to mixing different streams of single-phase coolant and two-phase coolant.

5 While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention.